Precursor turbulence and acceleration in shocks

Andrey Beresnyak,
Tom Jones, Alex Lazarian

Diffusive Shock Acceleration

shock

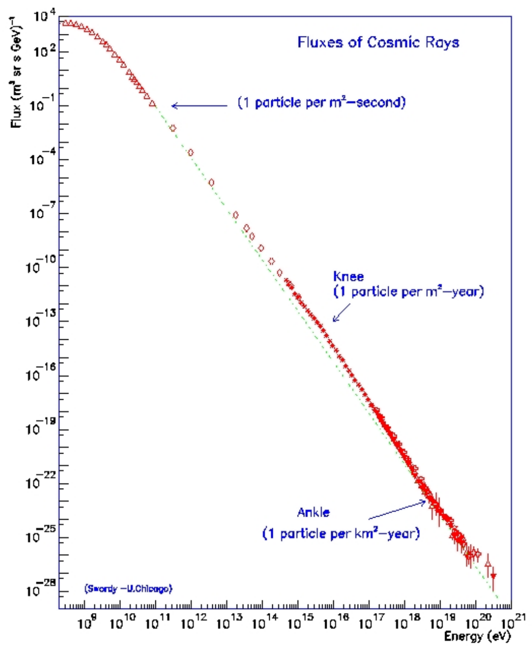
Scattering CRs in front of the shock is essential.

Krymsky, 1977
Axford et al, 1977
Bell, 1978
Blandford & Ostriker 1978

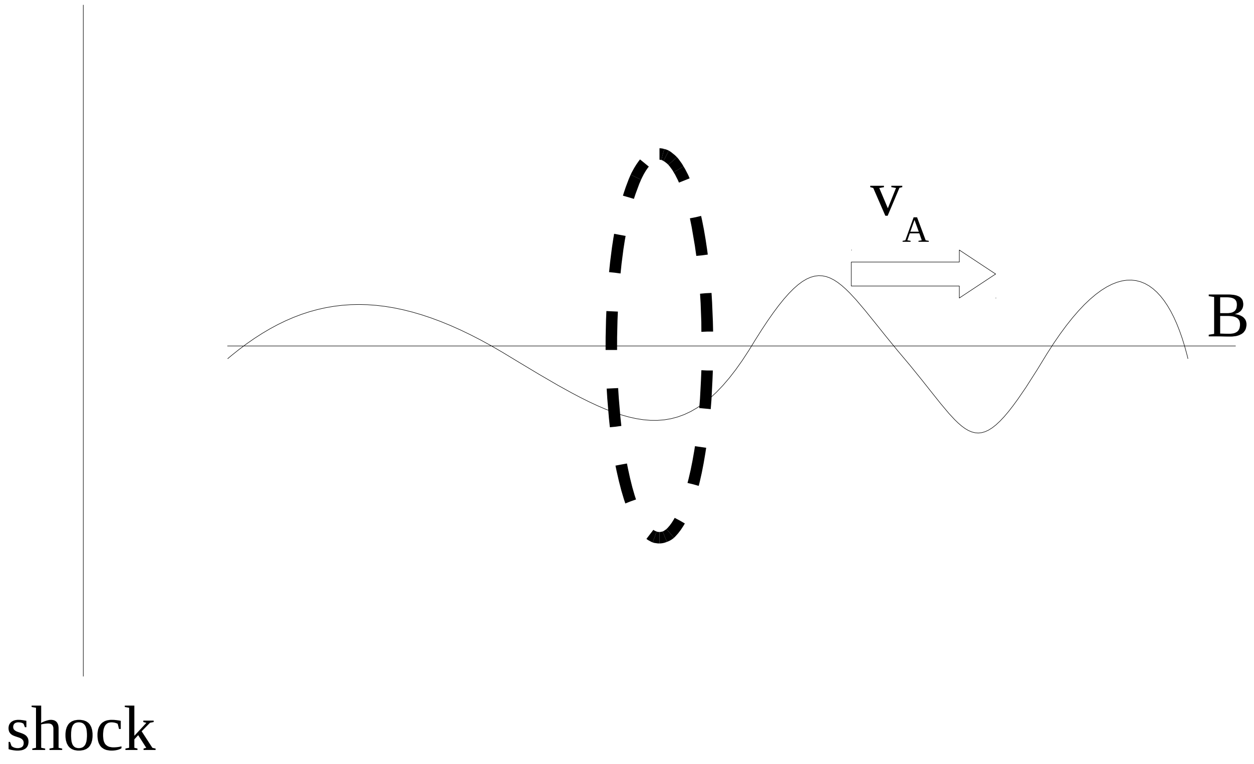
u_2 u_1

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial f}{\partial x}\right) + \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p}$$

$$f \sim p^{-\alpha}$$

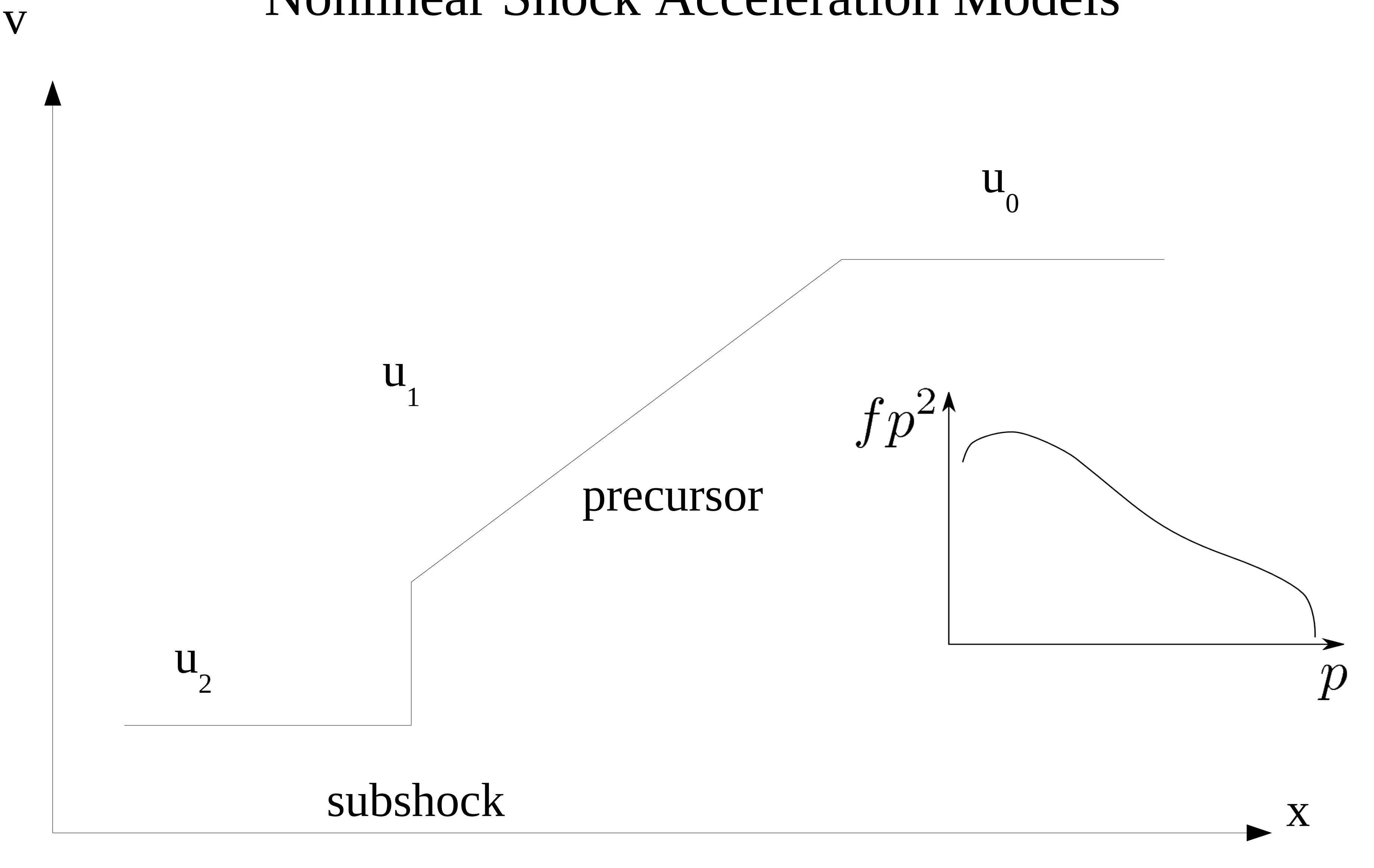


Streaming Instability in Front of the Shock



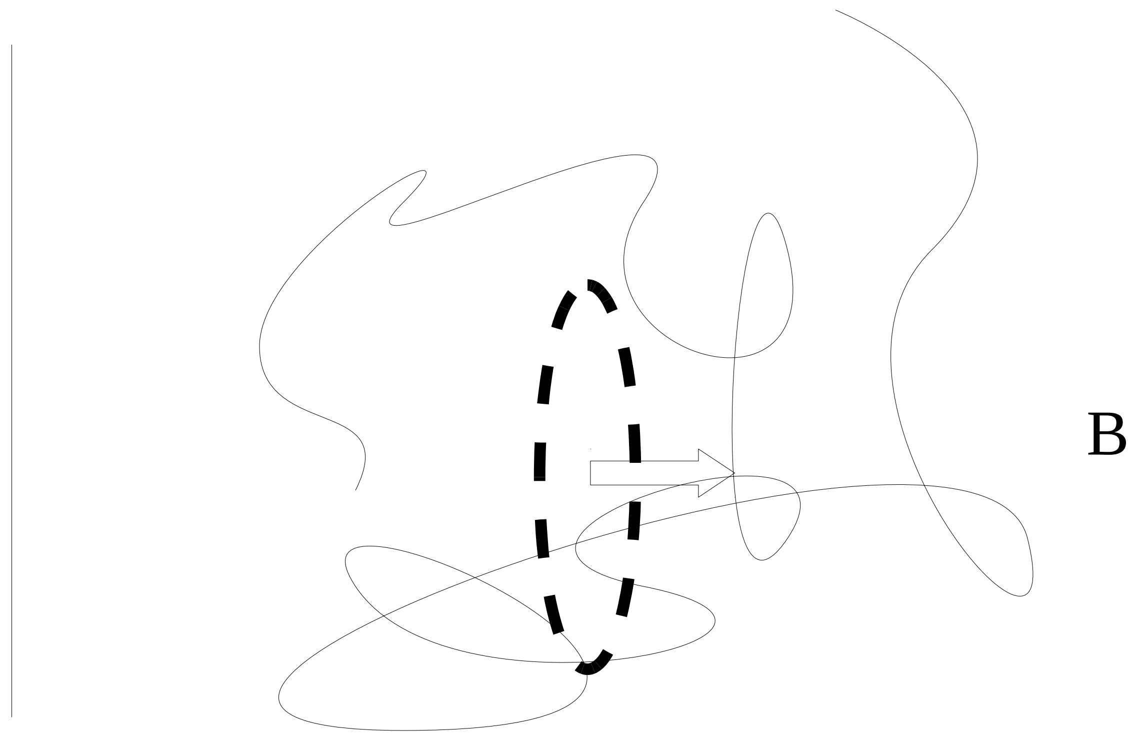
$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial f}{\partial x}\right) + \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

Nonlinear Shock Acceleration Models



See, e.g., review by Malkov & Drury (2001)

Nonlinear Streaming Instability



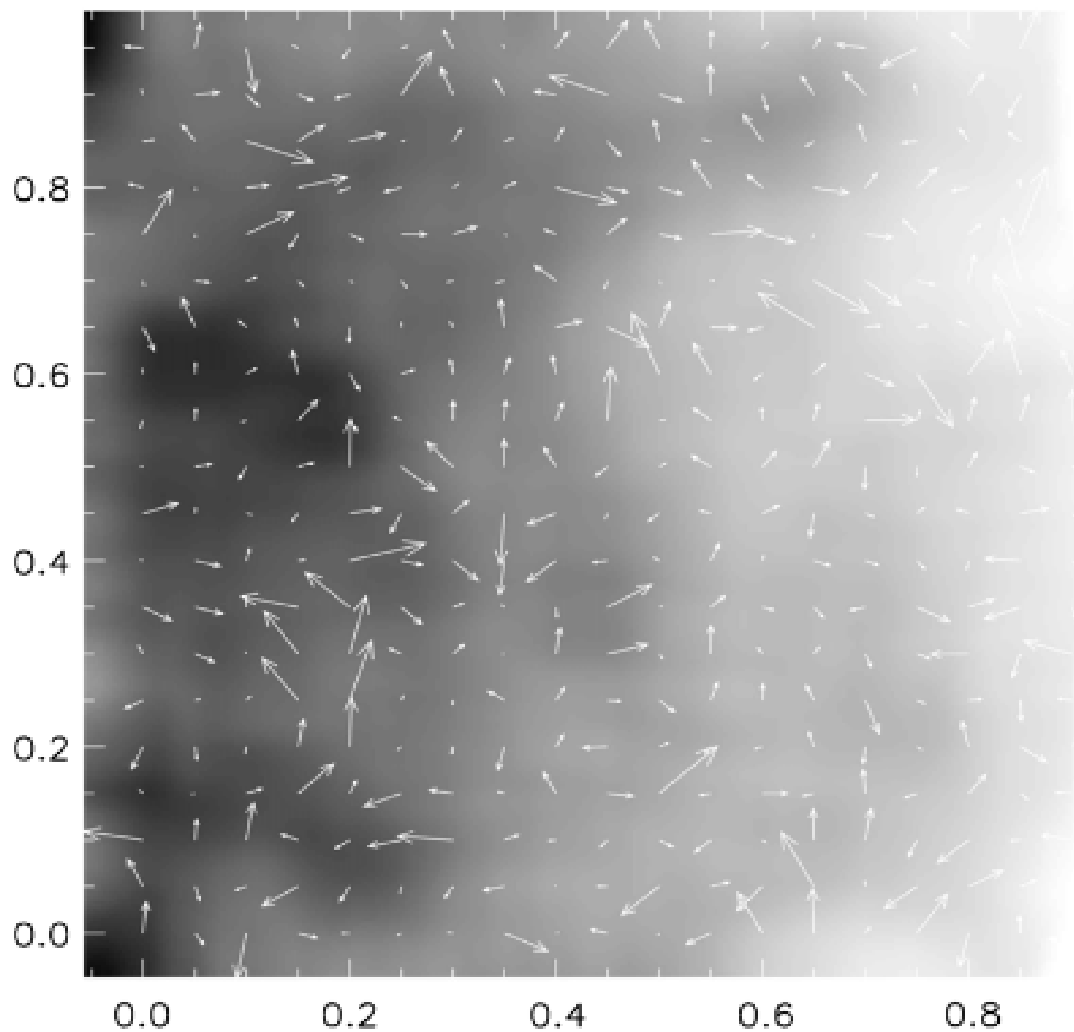
subshock

$\delta B \gg B_0$

Diamond & Malkov (2007)

Particle Tracing in Turbulent Fields

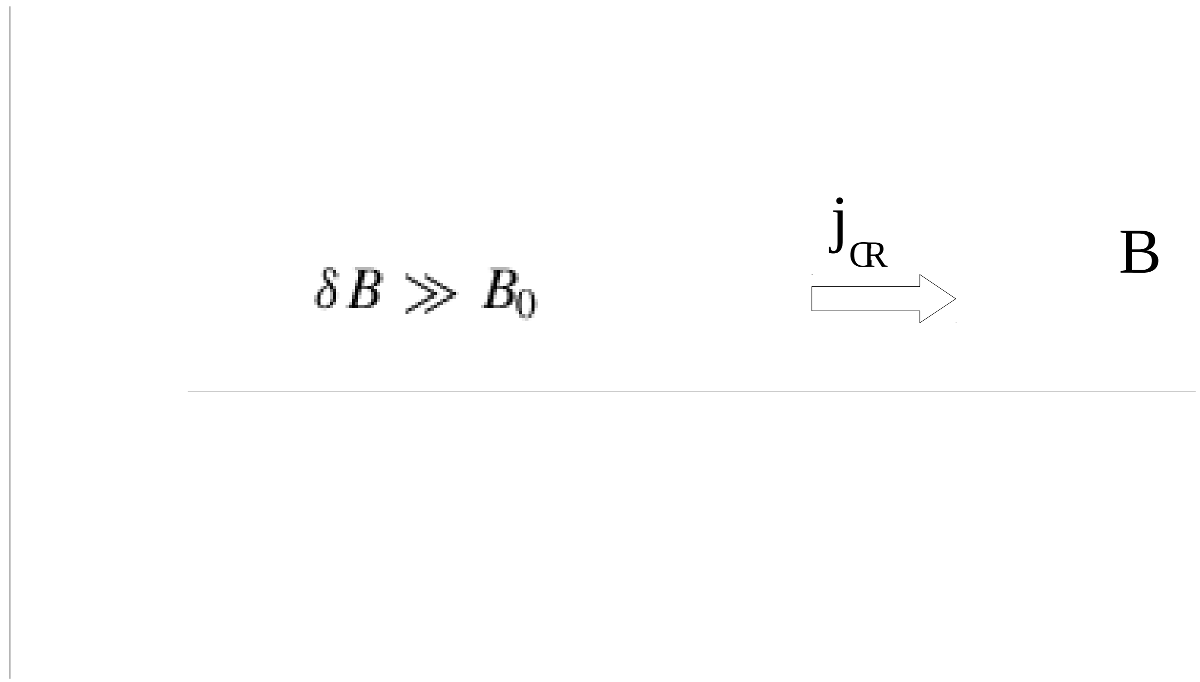
particles injected



particles escape

(slice from 3D)

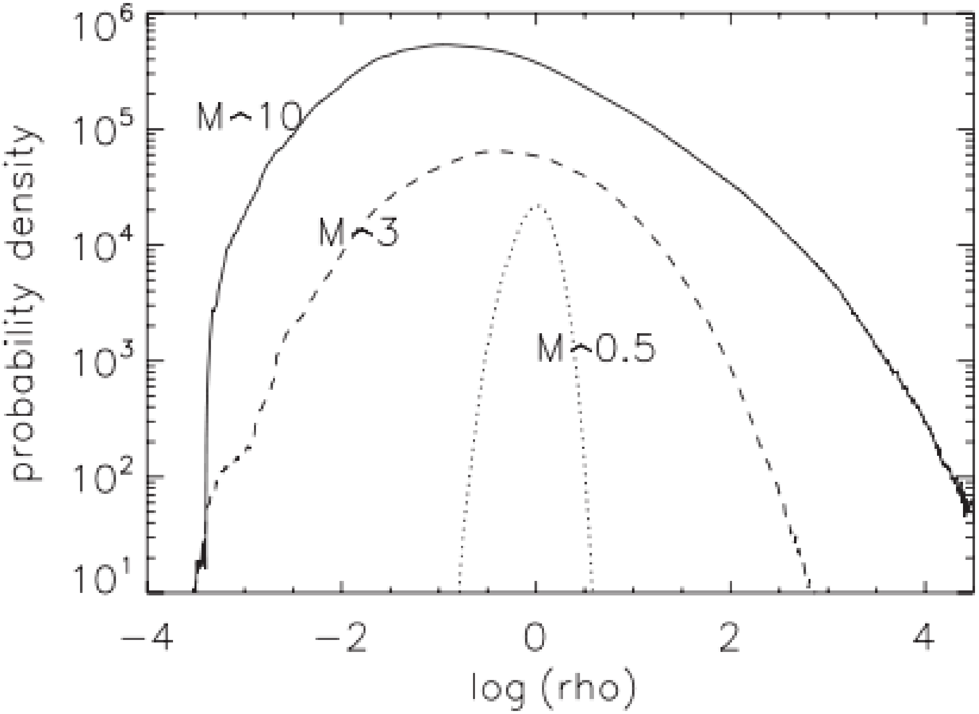
Current Instability



subshock

Bell (2004)

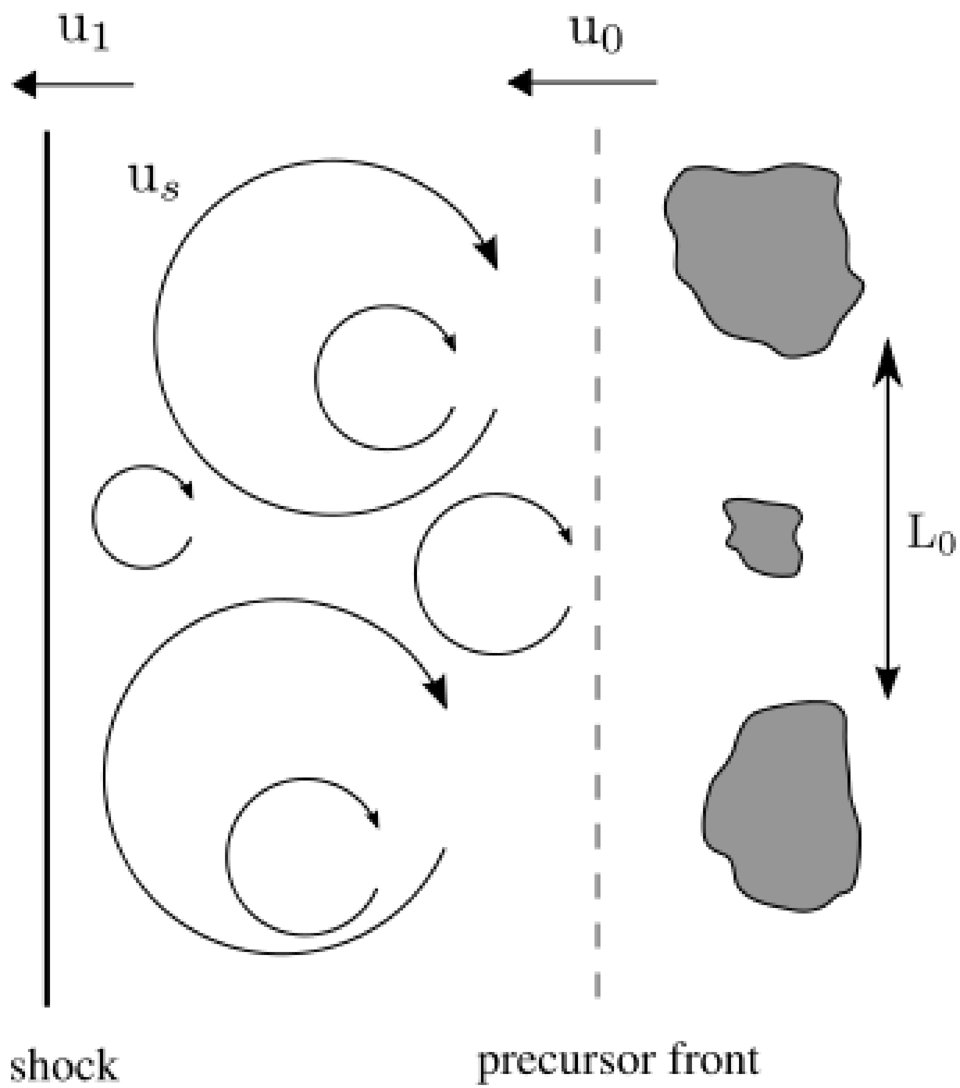
Density inhomogeneities in the ISM or stellar wind



(from Beresnyak & Lazarian 2005)

Crab Nebula (NASA, HST)

Precursor Turbulence

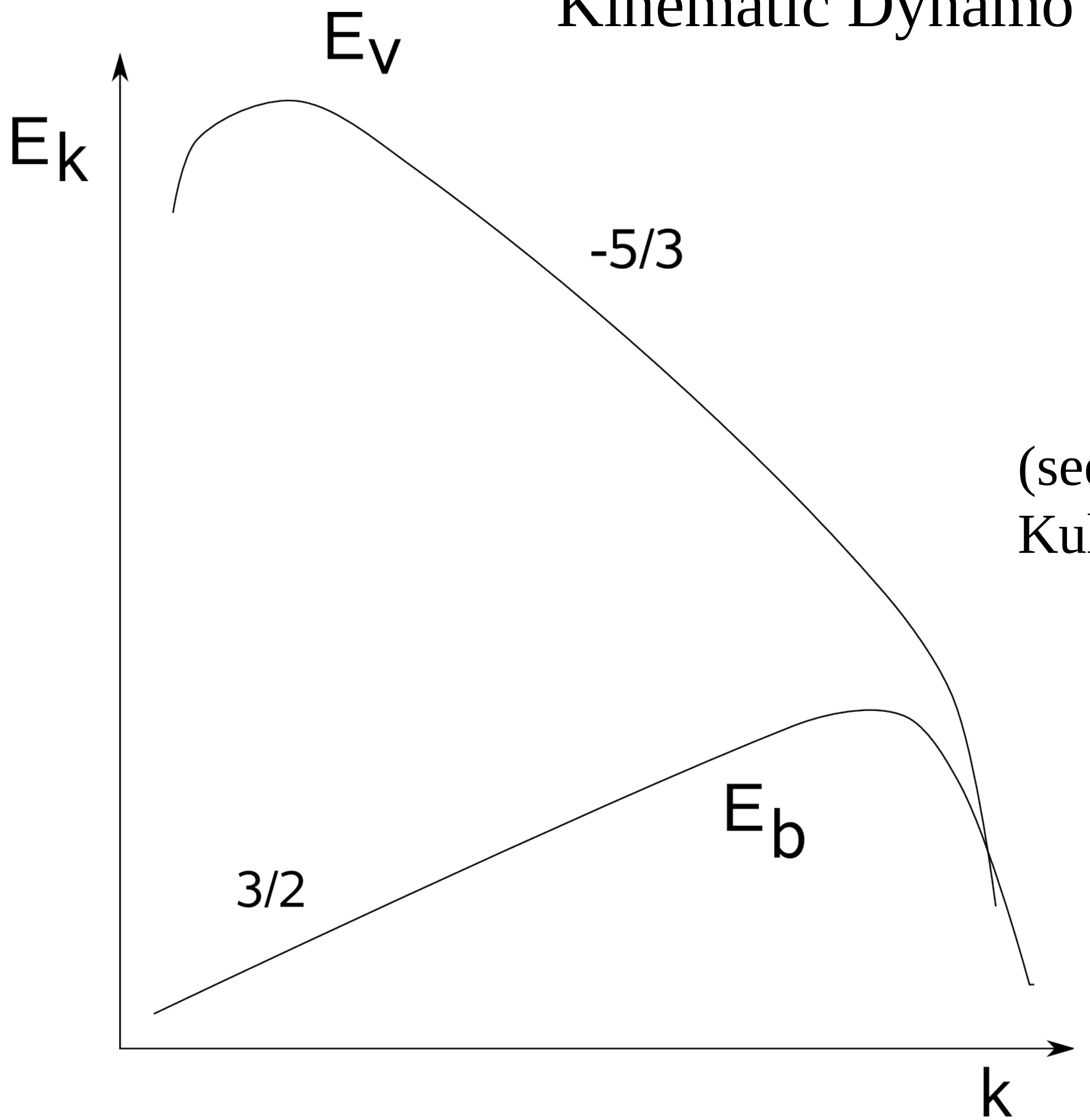


Large-scale dynamo,
require special conditions,
and slow

vs

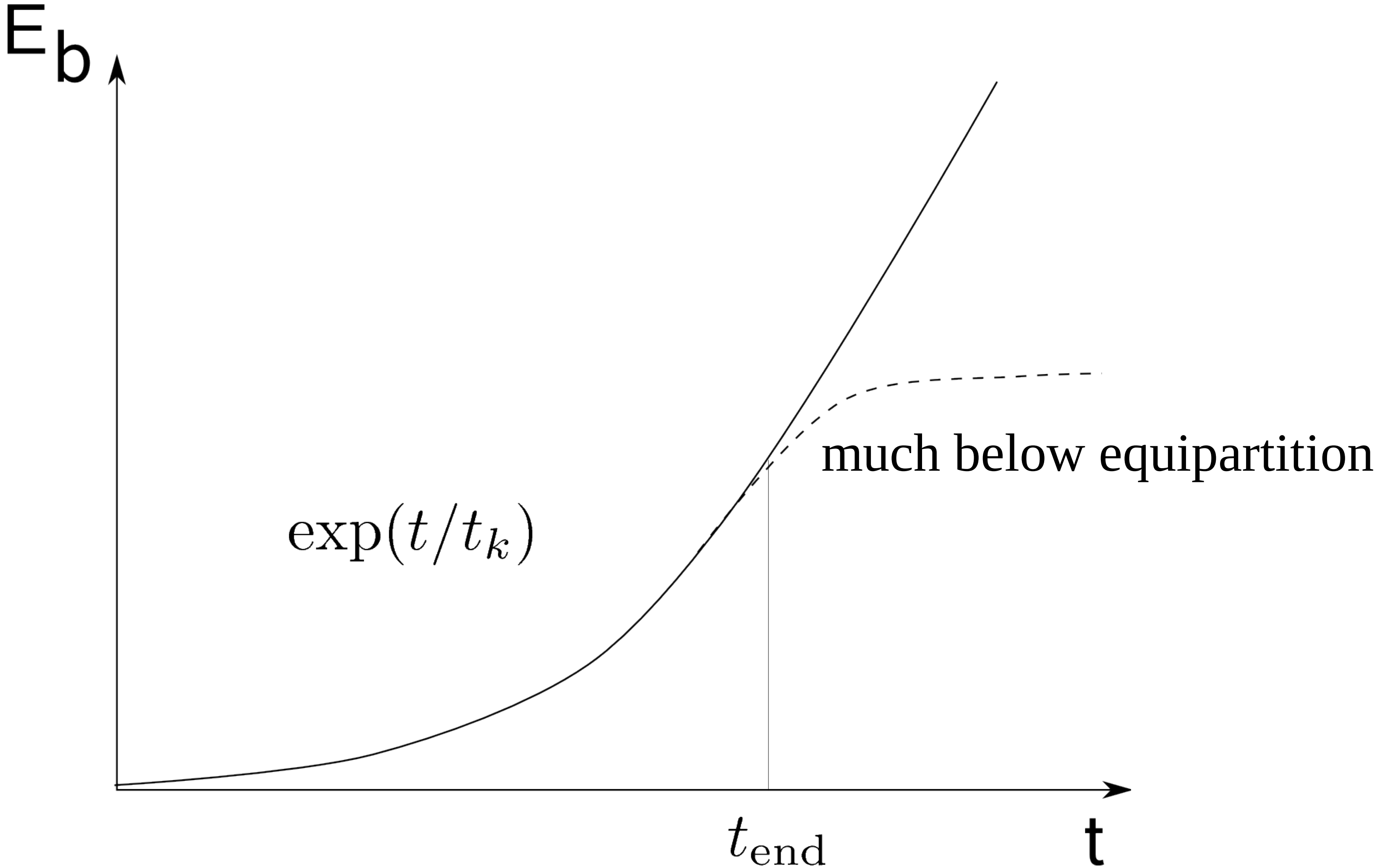
small-scale dynamo,
very generic in
three-dimensional dynamics
and fast

Kinematic Dynamo

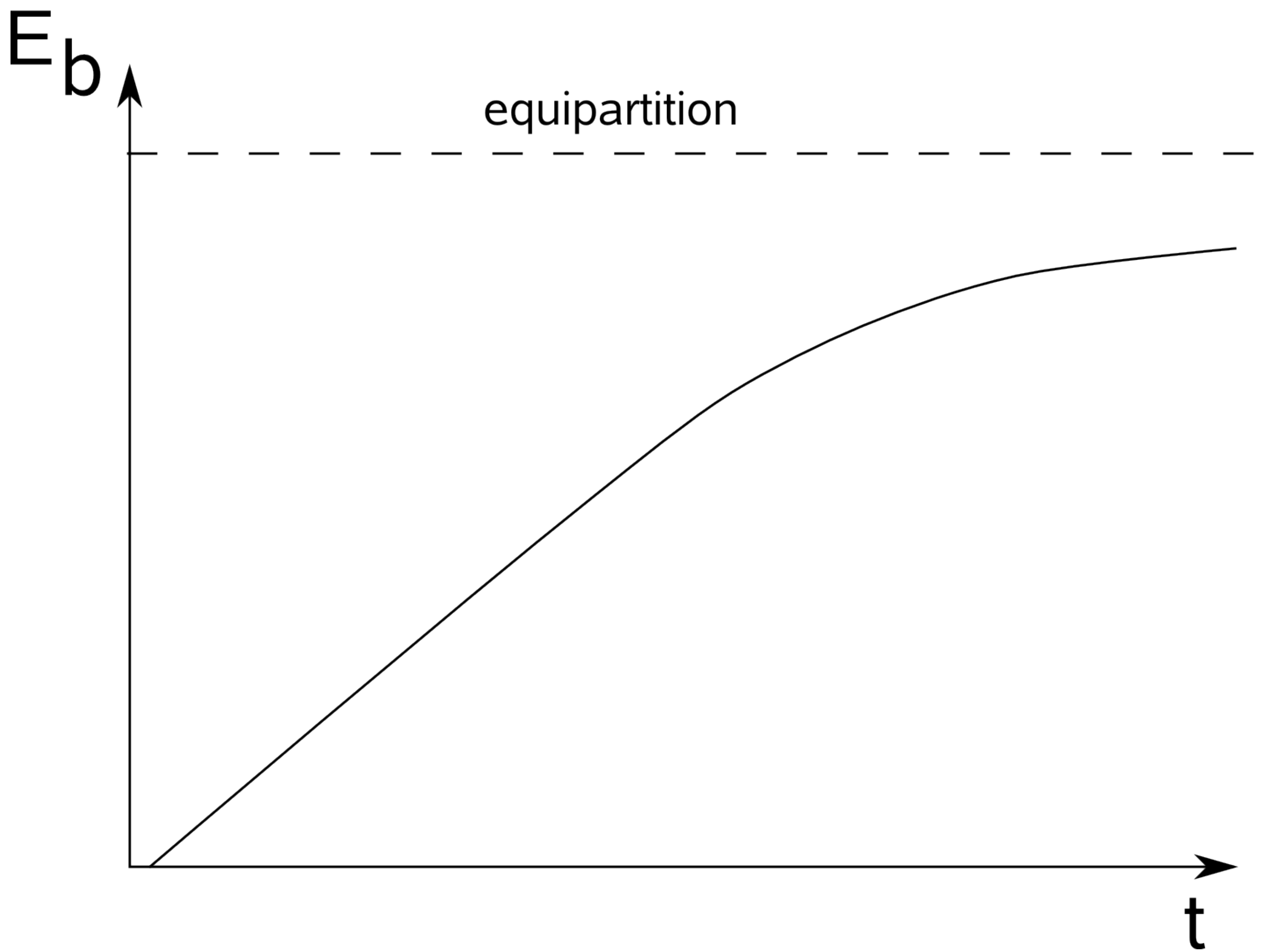


(see, e.g. Kazantsev, 1967, Kulsrud & Anderson 1922)

Kinematic Dynamo



Nonlinear Dynamo



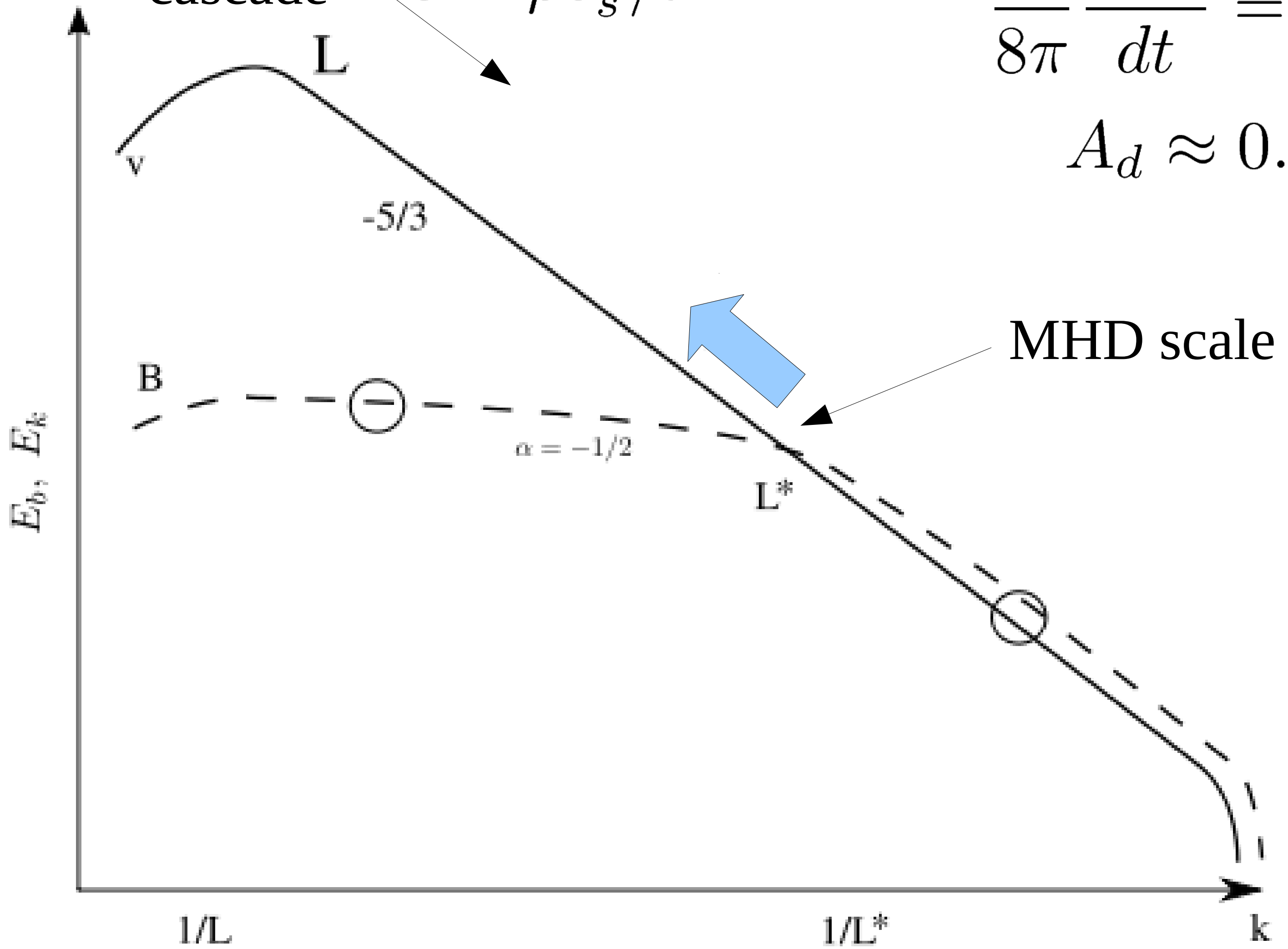
Nonlinear Dynamo

hydrodynamic cascade $\epsilon \sim \rho v_s^3/l$

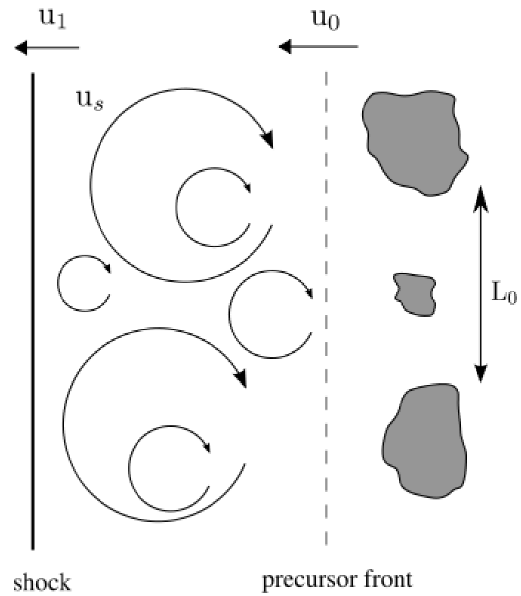
$$\frac{1}{8\pi}\frac{dB^2}{dt} = A_d \epsilon t$$

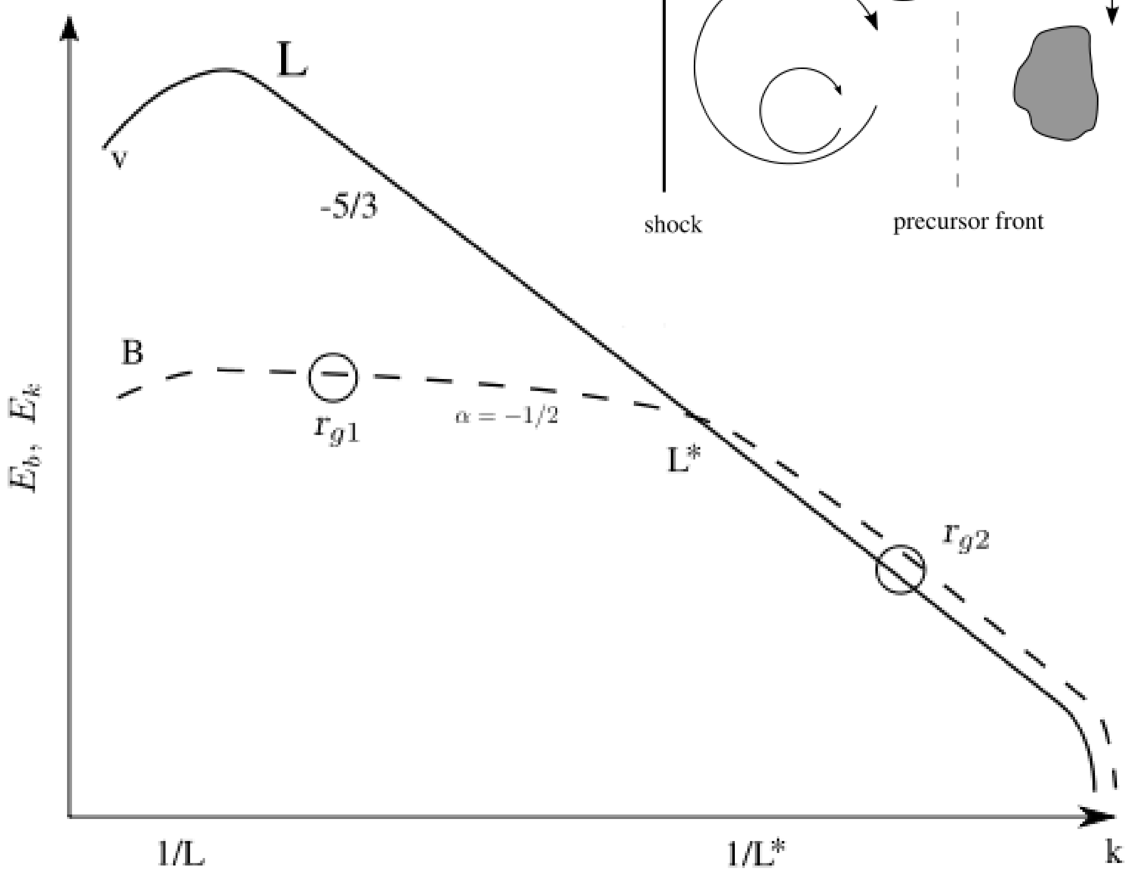
$$A_d \approx 0.06$$

MHD scale



Nonlinear Dynamo





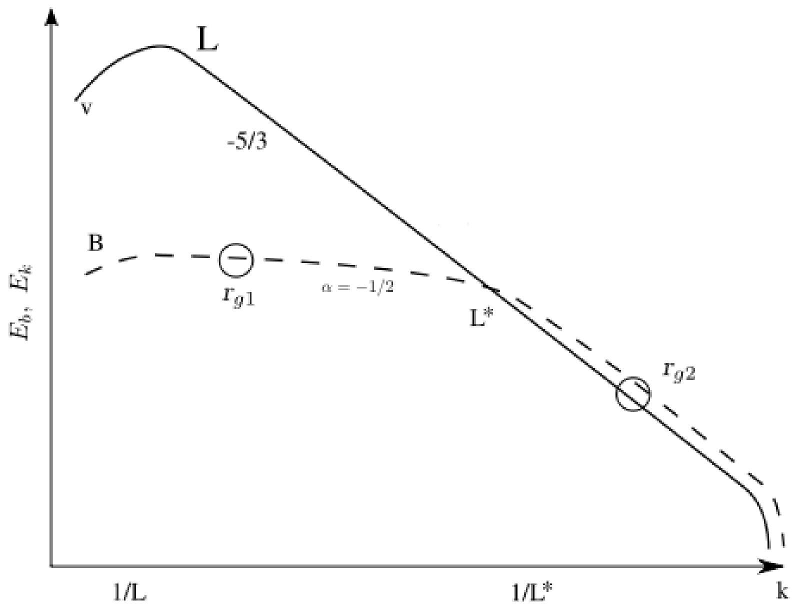
$$\delta B^2(L^*, x_1) = 8\pi A_d \epsilon \tau(x_1);$$

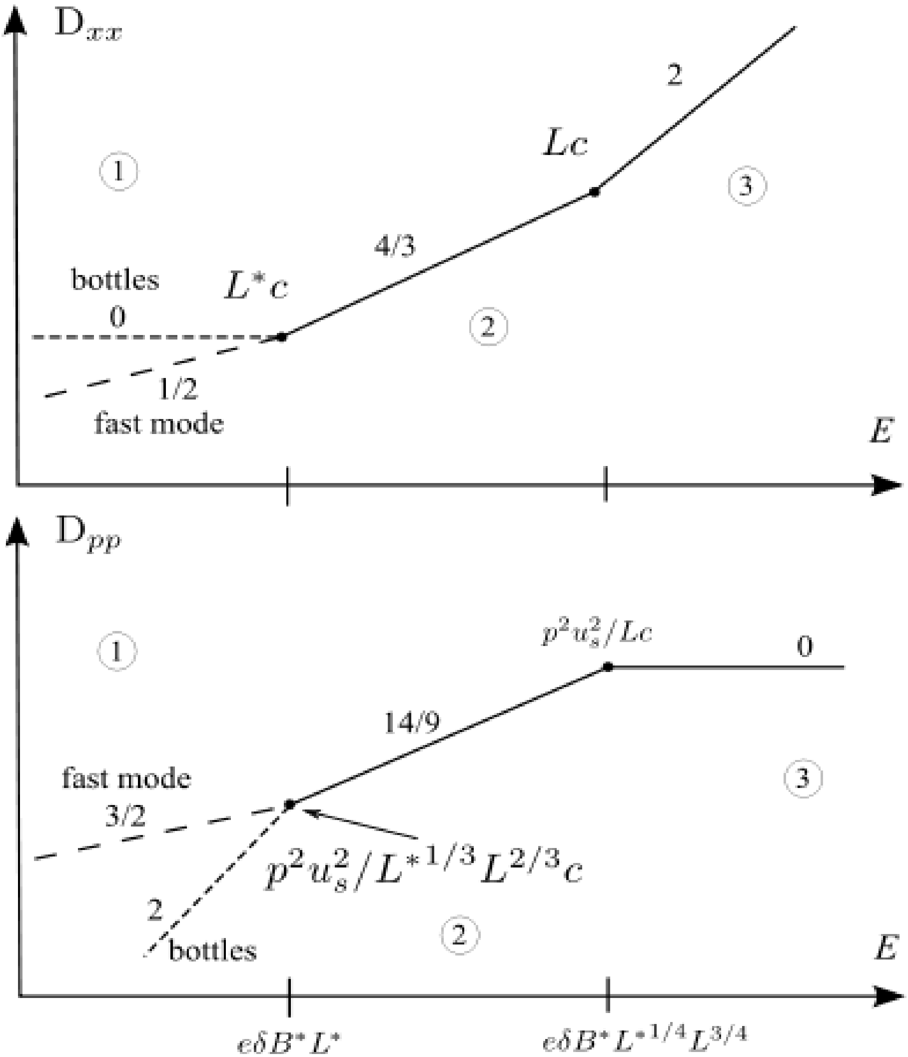
$$\frac{\delta B^*}{\sqrt{4\pi\rho}} = u_s \left(\frac{L^*(x_1)}{L}\right)^{1/3};$$

$$\tau(x_1) = \int_{x_1}^{x_0} \frac{dx}{u(x)};$$

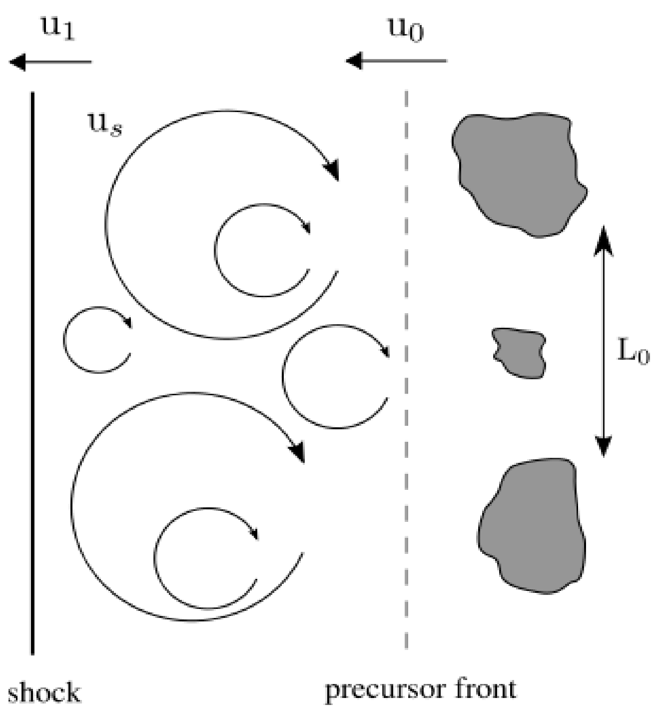
$$L^*(x_1) = (2A_d u_s \tau(x_1))^{3/2} L^{-1/2}.$$

Particle Scattering

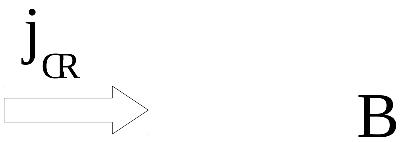




Comparison Between Small-Scale Dynamo and Current Instability



current instability



$$\frac{dB^2_{\rm cur}}{dB^2_{\rm dyn}} = 1.6 \times 10^{-4} \left(\frac{10^{15}\ {\rm eV}}{E_{\rm esc}}\right) \left(\frac{\eta_{\rm esc}}{0.05}\right) \left(\frac{L}{1\ {\rm pc}}\right) \times \left(\frac{B_0}{5\ \mu{\rm G}}\right) \left(\frac{v_{A0}}{12\ {\rm km\ s^{-1}}}\right) \left(\frac{0.5 u_{\rm sh}}{A_s(u_0 - u_1)}\right)^3$$

Summary

If fluid inflowing strongly modified shock has large density inhomogeneities, it develops turbulence and generates fairly strong magnetic fields which resolves the problem of particle scattering in front of the shock.

Future Work

We will quantify the amount of solenoidal motions with more precision using MHD simulations. We will solve coupled diffusion-advection and MHD fluid equations to obtain particle spectra and the structure of the precursor.

Sources of kinetic energy (and B, and CRs):
1. Directly from gravity (e.g., MRI)
2. AGN jets
3. Stellar winds
4. SN explosions